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Example of application in the department of Indre-et-Loire

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The VitiTerroir model to simulate the spatial dynamics of vineyards on the long term (1836-2014)

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EDITOR'S NOTE

This article is the translation of: Le modèle VitiTerroir pour simuler la dynamique spatiale des vignobles sur le temps long (1836-2014)

Introduction

1 VitiTerroir is a research program funded by the Centre-Val de Loire region (France) from 2014 to 2016. Today's wine-growing landscapes are the result of a several centuries, if not millenias of historical evolution, under the combined effect of cultural (changing tastes, a sense of identity with the vine, etc.), social (new consumer demands in terms of public health and well-being, etc.), economic (changes in demand, competitive pressure, etc.), legal (changes in legislation on planting rights, etc.) and environmental factors (soil impoverishment or erosion, landscape concerns, urban pressure, climate change, etc.). With the VitiTerroir model, we want to approach the dynamics of vineyards over the long term according to a systemic approach and on the scale of Touraine (department of Indre-et-Loire, where the Loire Touraine, Chinon, Vouvray, Montlouis, Bourgueil and Saint-Nicolas-de-Bourgueil AOC are located). On the basis of the founding reflection of Roger Dion (Dion, 1959), based on preliminary historical studies at the communal level (Lammoglia and Leturcq, 2017a; Leturcq et al., 2015), at the departmental level (Lammoglia and Leturcq, 2017b), at the regional and

national level (Legouy, 2014), it is necessary to identify the role of a few fundamental factors in the evolution of the municipal winegrowing areas from 1836 to 2014. The evaluation of the factors is carried out using a spatialized simulation model developed with the GAMA platform (Taillandier et al., 2012). More specifically, we study the influence of demography and wine consumption, the impact of the expansion of urban areas, the phylloxera crisis in the 1880s and 1890s, the AOC classification from the 1930s and the historical qualitative recognition of certain vineyards. The challenge of the model is to identify the conditions of resilience of current vineyards to social, cultural and economic shocks, based on an analysis of spatial dynamics between 1836 and 2014.

Geosimulation applied to viticulture, a state of the art

2 Agent-based modeling is a practice derived from complexity sciences at the crossroads of computing and distributed artificial intelligence. It emerged in the 1980s from the need to focus on systems capable of adapting to structural or environmental changes, and to take into account the complexity of the problems imposed by a local vision (Ferber and Perrot, 1995). To our knowledge, the sciences of vine and wine began to take possession of these tools at the beginning of the 21st century. We propose here a quick overview of the state of the art to locate the modelling work carried out within the framework of VitiTerroir.

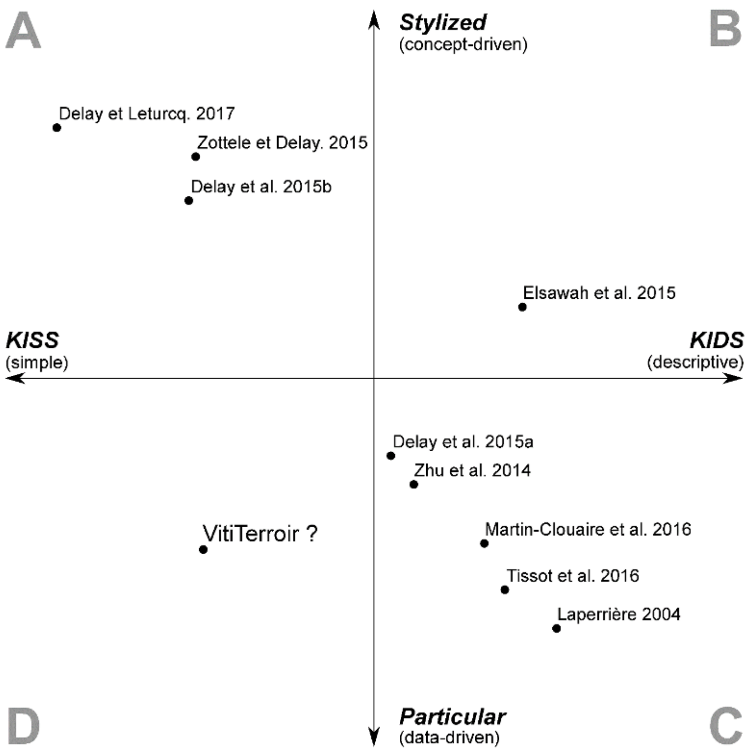
3 To do this, we use a graph proposed by Banos and Sanders (2013), which allows us to position different agent-based models relatively (Figure 1). The KISS (Keep It Simple Stupid) and KIDS (Keep It Descriptive Stupid) approaches are opposed on the abscissa (Edmonds and Moss, 2004), while the concept-driven and data-driven models are opposed on the ordinate, giving us a graph with four quadrants (A-B-C-D). We present some works involving SMAs (Multi-Agent Systems) to reflect on viticultural issues.

4 Quadrant A of Figure 1 highlights models developed to serve as a "crutch for the human mind" (Banos, 2010). It is not strictly speaking based on quantitative data and aims more to demonstrate and explore spatial dynamics in a theoretical way. This is the case of the CiViSMe model (Delay et al., 2015) which shows the influence of cooperation on a stylized mountain wine system. The ViCTor model (Delay and Leturcq, 2017) focuses in a very abstract way on the effects on the dynamics of wine-growing landscapes of competition between food crops (cereals) and perennial crops (vines). Finally, in the same quadrant, the model presented by Zottele and Delay (2015) focuses on the effects of spatial isolation of viticultural practices on cultural practices. The B-quadrant models maintain a number of stylized mechanisms, but focus on more accurately describing social interactions. The work described by Elsawah et al (2015) formalizes winegrowers' decision-making; while being more descriptive of decision-making mechanisms, abstraction retains a prominent place in the model. Quadrant C contains the majority of the works identified. These have a very strong local base. The work of Martin-Clouaire et al (2016) and Tissot et al (2014) focuses on the formalization of winegrowers' decision-making in a detailed way. Zhu et al (2014) also work at a fine scale on the influence of climate change, as does the AcidityGIS model (Delay, 2015). Laperrière's (2004) work, at the individual level, focuses on the influence of social interactions (respectively between individuals and with the cooperative). At this stage, the VitiTerroir model falls within Quadrant D, because we have chosen to work on a

model that is relatively abstract in its level of aggregation, while trying to reproduce a pattern dictated by data from our collection work (geolocated geographical data; vineyard areas for each municipality for several years from the 19th and 20th centuries to 2014; demographic data).

5 The VitiTerroir model belongs to the KIDS family of models and is positioned in Quadrant D. It is based on data from vineyard areas collected for the period 1808-2014, both demographic and consumption data, but working at an aggregated simulation level (municipal resolution). The factors implemented are not exhaustive and the description of the evolution mechanisms is as simple as possible while being very strongly anchored in the territory.

Figure 1: typology of some models applied to viticulture according to the grid proposed by (Banos and Sanders 2013)



Research questions

6 The VitiTerroir programme is driven by the desire to find the evolution factors that would make it possible to characterise the dynamics of the Tours vineyards over the long term. Based on the last two centuries, are there any determining factors? If so, which ones? By modelling these factors, can we design a simulation tool that is precise enough to trace the past evolution of wine-growing areas?

7 The first objective of this work is to model four factors identified previously as important, namely (i) the evolution of wine consumption per inhabitant combined with the French demographic evolution, (ii) the polarization of vineyards by some historical production centres (theory of elite cores and AOC delimitation) (iii) the expansion of urbanized areas that we analyze through the evolution of population density per commune and (iv) the phylloxera crisis (since 1882 in Touraine) (Tessier, 2010). We are

aware that these factors are not exhaustive. For example, social structures such as winegrowers' groups have certainly played an important role. However, at this stage of the research and in the absence of adequate data, it is impossible to integrate them into the model. The second objective is to evaluate the accuracy of the model and its ability to understand the spatial dynamics of vineyards from a retrospective perspective.

Presentation of the model

8 The VitiTerroir model simulates the evolution of the wine-growing areas of the communes of Indre-et-Loire from a time t0 (1836) to a time tfinal (2014). The wine-growing areas are calculated year by year, according to a general equation integrating factors at the global (France and department) and local (commune) levels. The model incorporates four factors that we detail here.

- The evolution of per capita consumption combined with the French demographic evolution. This factor, which represents the demand for wine, has a homogeneous effect on all municipalities.
- The distance of each commune from historical wine-growing cradles, known as "elite cores". According to the theory of Georges Kuhnholz-Lordat (1963), we hypothesize that a vineyard is all the more resilient when it is close to an elite core. From 1936-1939 onwards, the municipalities were also affected according to their situation in relation to the delimitations of the AOC areas set up by the INAO. This factor introduces spatial differentiation at the scale of the territory and makes it possible to distinguish between municipalities with a wine-growing activity favoured by regulations.
- The expansion of urbanized areas that we analyze through the evolution of population density in each municipality. This factor makes it possible to identify the communes that have potentially experienced significant spatial competition between the vine and the city since the second half of the 20th century. For example, the population of Joué-lès-Tours increased tenfold between 1926 and 1982.
- The phylloxera crisis, which led to a sudden drop in wine-growing areas (about 45%) at the end of the 19th century.

Spatial and temporal resolution

9 We simulate the evolution of wine-growing areas at the level of the Indre-et-Loire department and with a communal resolution. The 273 municipalities are modelled as agents in the GAMA platform. The time step of the simulation is the year (one iteration = 1 year). The simulation time is variable, we define it according to the period to be simulated. For this article, we have focused on the 1836-2014 period, which is the longest period for which we have reliable data.

Description of the agents

10 The model integrates a single category of agents: municipalities. Agents have no cognition or interaction ability. Each commune is characterised by an initial quantity of vines, a distance from the nearest elite core, whether or not it belongs to an AOC area and a population dynamic (change in population density).

Formalization of the model

11 The evolution of the communal wine-growing areas is calculated by means of an equation, identical for all communes, integrating the four factors. At each iteration, the 273 communes execute the following equation and update their SurfaceVigneSimut+1 variable:

12 At each iteration, the 273 communes update their SurfaceVigneSimut+1 variable.

13 The weighting on the variables *CoefConso*, *CoreDistance* and *CoefDensity* allows the model to be calibrated via the simulation interface. Knowing that the demand for wine is always formalised by the multiplication of *CoefConso* and *CoefPop* (consumption is expressed in l/year/inhabitant), it is not necessary to give weight to *CoefPop*. *CoefAOC* is also not weighted, as it is a constant that we have empirically defined.

Evolution factors and model configuration

14 The model takes into account four factors. Below we explain how they are integrated into the model and what data they use if any.

Consumption and demographics: the demand for wine

15 The first factor is a high-level process, i.e. one that has the same impact on all municipalities. This is French wine consumption, estimated from gross consumption measured at the national level (expressed in l/hab/year) combined with French population growth. The rates of change of the two variables affect the wine-growing areas of each municipality proportionally. We thus use two equations that model the observed evolutionary trends from real data (Figures 2 and 3). To take into account the different phases of growth and decline, we have divided the 1836-2014 period into three different sub-periods for consumption and demography.

Figure 2: Evolution of French wine consumption (l/hab/year) according to three sub-periods.

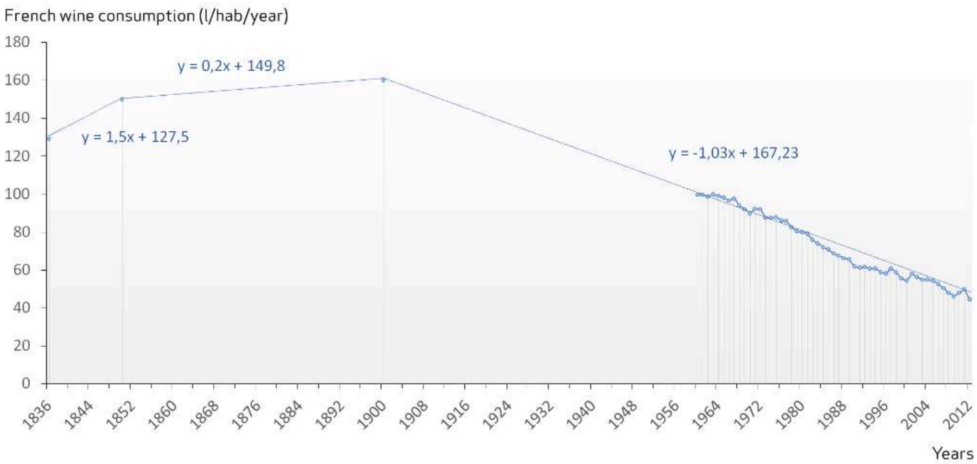
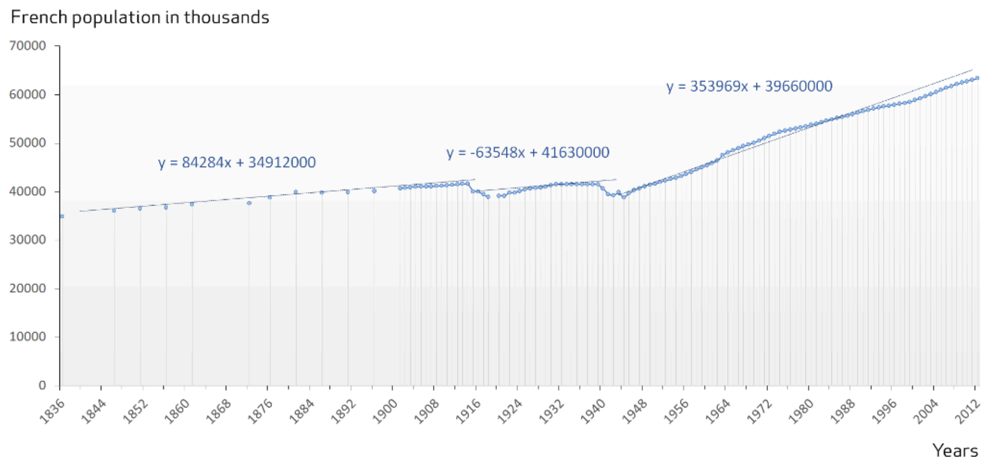


Figure 3: Evolution of the French population according to three sub-periods



16 We then calculated the refined function of the trend curves for each sub-period. For the sake of simplicity, the model calculates the evolution of the two variables from these affine functions and not from the actual data. Depending on the simulated period, the model adjusts the function as follows:

17 Consumption :

- 1836-1850: y = 1.5x + 127.5
- 1850-1900 : y = 0.2056x + 149.49
- 1900-2014: y = -1.0916x + 167.23

18 Demographics :

- 1836-1914: y = 84284x + 3491200
- 1914-1945: y = 15770x + 40000000
- 1945-2012: y = 345581x + 40000000

19 Thus, according to these affine functions, the model calculates at each iteration the evolution rates of consumption and the French population which, once integrated into the general equation, make it possible to obtain the wine-growing surface at t+1 as a function of that at t.

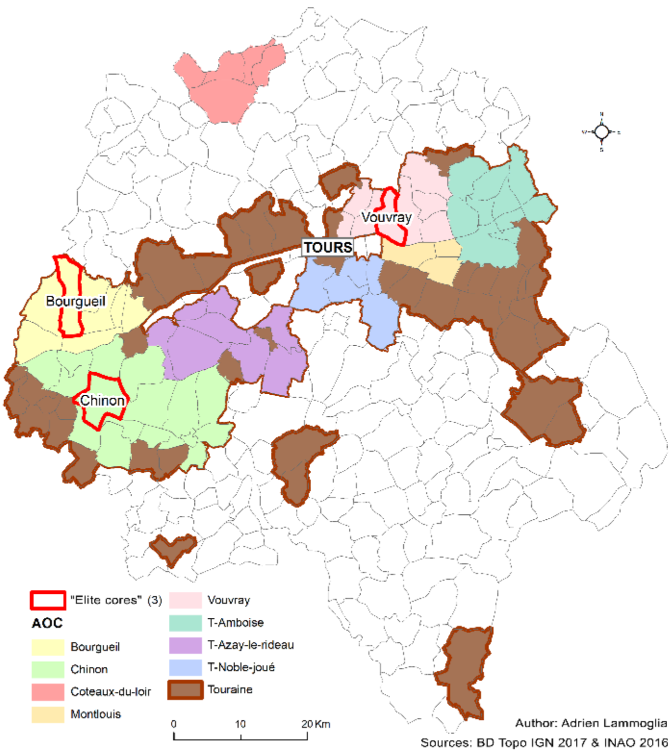
Polarisation of the wine-growing area: the theory of elite cores and AOC delimitations

20 The second factor makes it possible to integrate a spatial differentiation based on the theory of "elite cores" proposed by Georges Kuhnholtz-Lordat in 1963 as a theorization of the principle of delimitation of AOCs. According to the author, there are stable wine-growing poles over time, identifiable thanks to the widely shared reputation for quality of the wines produced. The author introduces the idea that the quality of the wines produced decreases as the distance between the vineyards and the core increases. The cores appear as resilient production poles: "The quality decreases, on the whole, when one moves away from the initial core of the vineyard installation. If viticulture goes through periods of decline, this core defends itself better" (Kuhnholz-Lordat, 1963, p. 32).

21 In a previous work (Lammoglia and Leturcq, 2017b), the historical analysis of the Touraine vineyard enabled us to highlight several "elite cores": the communes of

Vouvray, Chinon and Bourgueil (map 1). At initialization, the model identifies the nearest elite core for each commune, then calculates the Euclidean distance between them. During the simulation, the further away a commune was from the elite core, the more likely it was to lose in vine quality. Elite cores, on the other hand, are not affected by this coefficient.

Map 1: Location of AOC boundaries and elite cores identified for the simulation



22 From the second half of the 20th century onwards, the communes located in an AOC area experienced some wine growth. To model this differentiation, the communes are grouped into three categories, each characterized by a coefficient reflecting their capacity for resilience, or even wine growth, depending on the AOC area to which they belong:

- municipalities not located in an AOC area, which do not experience any particular wine growth (coefficient = 1);
- the municipalities located in the AOC Touraine and mentioning Touraine (Azay-le-Rideau, Amboise, Mesland), which are subject to a first coefficient (1.03) from 1939 onwards;
- the municipalities located in one of the main AOCs (Vouvray, Bourgueil, Saint-Nicolas-de-Bourgueil, Chinon and Montlouis), which are subject to a second, slightly higher coefficient (1.05) from 1939 onwards.

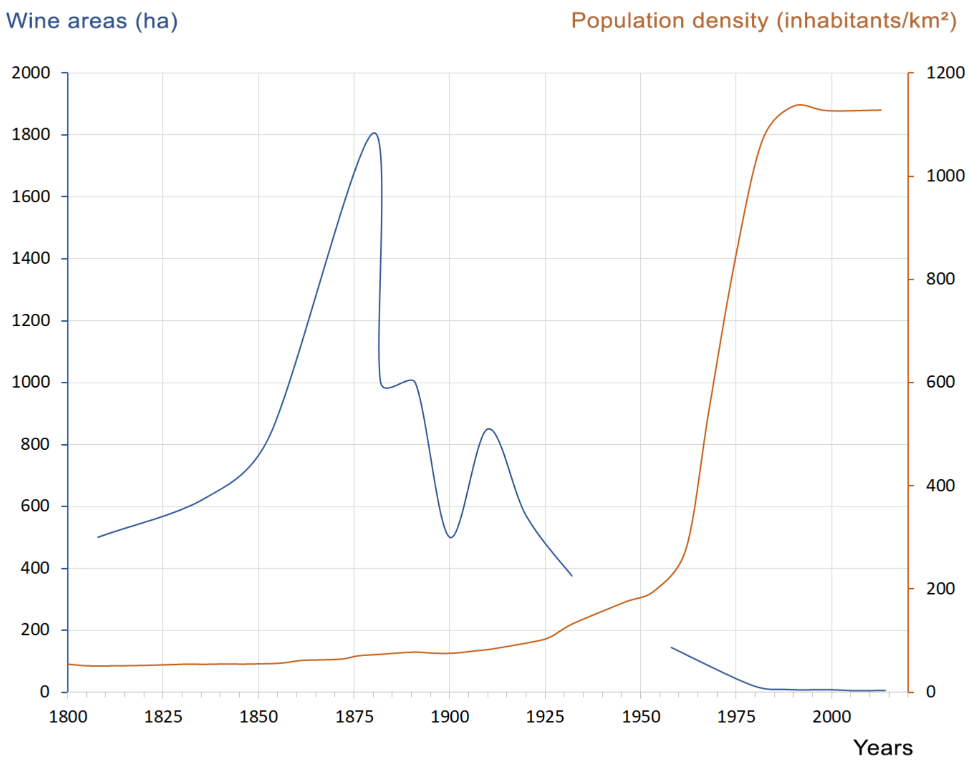
23 The AOC coefficient is a constant parameter that we have empirically defined using the model exploration functions of the GAMA platform.

Urban growth analysed through the evolution of population density

24 The third process also operates at the local level. It makes it possible to identify municipalities that have experienced strong population growth where, potentially, urban growth has had a negative impact on vineyard dynamics. We hypothesize that

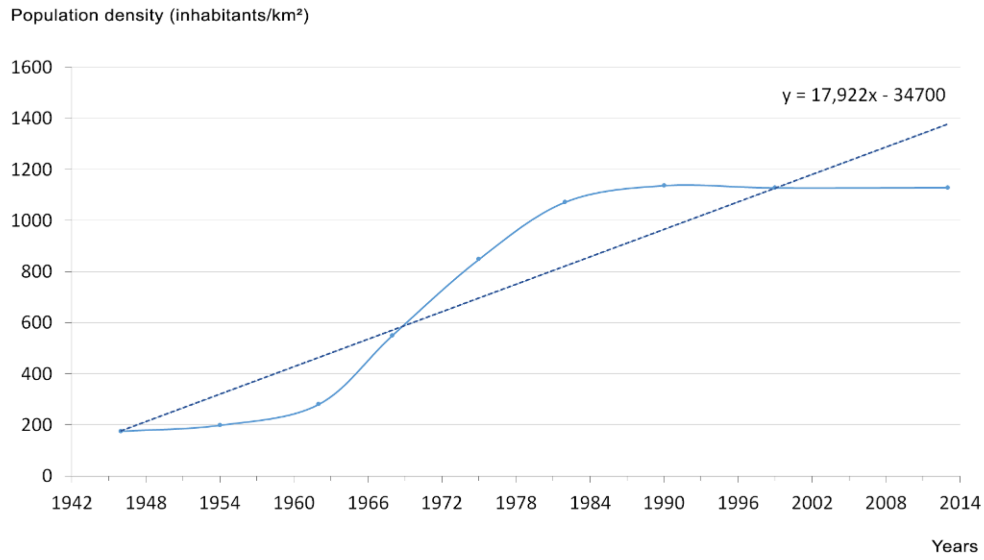
the municipalities that experienced rapid and significant population growth during the 20th century experienced significant urban growth and therefore a potential artificialization of agricultural land, particularly vineyards. To identify these high-growth municipalities, most of which are located in the Tours area (for example: Joué-lès-Tours), we calculated the rate of change in population density between 1946 and 2013 for each municipality. We chose this period because we found that strong population growth generally occurred after the Second World War (Figure 4).

Figure 4: Wine-growing areas and population density in Joué-lès-Tours



25 For each commune with a density change rate greater than 1, we calculated the affine linear adjustment function (Figure 5). Although the linear trend curve is not always the most representative of the observed dynamics, it seemed sufficient to us to compare the intensity of growth between the municipalities concerned. In addition, it allows us to integrate a rate of change into the model relatively easily.

Figure 5: affine function of linear adjustment for the evolution of population density at Joué-lès-Tours



26 In the model, we thus calculate the rate of change in density from 1946 onwards and integrate it into the denominator of the general equation. Thus, the higher the density growth of a commune, the more vineyards it lost. Among all the municipalities, we can distinguish the case of Tours, which has a unique profile. Indeed, the municipality has experienced sustained population growth since the beginning of the 19th century, which then increased in the second half of the 20th century. This particular case is also taken into account by the model by calculating the affine linear adjustment function for two periods: 1836-1945 and 1946-2014.

The phylloxera crisis

27 To take into account the sudden drop in wine-growing areas caused by phylloxera over the 1880-1900 period, we calculated, from the prefectoral sources kept at the Indre-et-Loire Departmental Archives (Lammoglia and Leturcq, 2017b), the loss observed at the departmental level that we applied to all the communes in a uniform way. Thus at the time t = 1900, each commune suffers a loss of 45% of its wine-growing area.

Summary of factors

Factors	**Description**	**Spatial resolution**	**Time range**	**Reliability of data**
1. Consumption and demographics	The combination of these two variables represents the general demand for wine	Global level (national data)	1836 to 2014	Fairly good (scattered consumption data for the 19th century)

2. Elite cores and AOC delimitation	The departmental territory is polarized by production areas with a certain reputation	Local level	1836 to 2014 for polarization by elite cores 1937 and 1939 to 2014 for AOC areas	Elite cores: inspired by theory and historical data AOC delimitations: perfectly reliable data
3. Urban growth	The potential competition between the city and the vine is modelled through the evolution of population density by commune	Local level	1946 to 2014 for all municipalities except the Tours conurbation, which experienced strong earlier growth (1836-2014)	Fairly good: factor based on demographic trend curves
4. The phylloxera crisis	The aim is to take into account the brutal destruction of vineyards caused by phylloxera at the end of the 19th century	Overall level (percentage of destruction applied uniformly to all municipalities)	The loss occurs at time t = 1900	Fairly reliable: based on the loss observed with departmental data

Description of the variables

28 The following table describes the main variables of the model. We distinguish between global and local variables, specific to each of the 277 communes.

Global variables

Name	**Description**	**Nature**	**Initial value**
CoefConso	Coefficient used to simulate the rate of change in French wine consumption	Variable	1.00241418 (calculated from actual data)
CoefPop	Coefficient used to simulate the rate of change in the French population	Variable	1.01176474706 (calculated from actual data)
AOCfactor	Resilience factor assigned to municipalities located in a WCA area	Constant	1 then takes the value 1.05 from 1937 onwards (empirically determined value)
MentionFactor	Resilience factor assigned to municipalities located in a Touraine AOC area and mention of Touraine	Constant	1 then takes the value 1.03 from 1939 onwards (empirically determined value)

Local variables (communes)

Name	**Description**	**Nature**	**Initial value**
CoefDensity	Coefficient used to simulate the rate of change in the communal population density	Variable	The variable keeps the value 1 until 1946, then is updated at each iteration based on the population dynamics observed in the real data
CoreDistance	Euclidean distance between each municipality and its nearest elite core	Constant	Varies according to the location of the municipalities
EliteCores	Variable allowing the differentiation of elite cores from other communes	Constant	1 for elite cores 0 for other municipalities
SurfaceVigneSimu	Wine-growing areas simulated by the model at time t	Variable	Varies according to the municipalities
SurfaceVigneInit	Wine-growing areas observed in 1836	Constant	Varies according to the municipalities
SurfaceVigneReel	Wine-growing areas observed in 2014	Constant	Varies according to the municipalities

Indicators for assessing the quality of simulation results

29 The model makes it possible to calculate at each time step the areas planted per commune. To facilitate the cartographic representation, we work with the vine density that we obtain by dividing the planted areas by the surface area of the communes (provided by the IGN's Topo database). To assess the accuracy of the model, we calculate the differences between the simulated and actual wine-growing areas. These differences cannot be analysed for each simulated year, as we do not have the actual surfaces for the entire 1836-2014 period. On the other hand, we compare the simulated data with the 2014 vineyard register, which is the most reliable and recent database available to us.

30 To analyze these variations, we use the following statistical indicators:

- average of the differences between municipalities (ha): indicates the average of the differences between the municipal wine-growing areas (simulated - real)
- median of the differences between municipalities (ha): indicates the median of the differences between the municipal wine-growing areas (simulated - actual)
- standard deviation of municipal deviations (ha): indicates the standard deviation of deviations of municipal wine-growing areas (simulated - actual)
- average index: we average the three previous indicators; it is this indicator that we will try to minimize during the exploration of the model (the lower the indicator, the more accurate the model).

Exploration of the VitiTerroir model

31 To explore the model, we used the sensitivity analysis function provided by GAMA. We seek to minimize the average index. As a reminder, a low average index means that the differences between simulated and actual data are small, and therefore the model is accurate. To this end, we used the POM method (Pattern Oriented Modeling[Grimm et al., 2005]), which consists of first integrating the first factor (consumption) into the model, then adding the second factor (wine cores and AOC delimitation) and so on until the four combined factors are integrated. The advantage of this method is that the model improves step by step, while limiting the number of simulations to be performed for its configuration.

Consumption and demographics (sub-model 1)

32 For the first factor, we vary only one parameter, it is the weight assigned to the consumption variable. This weight varies from 1 to 10 in steps of 0.1, resulting in a total of 91 simulations.

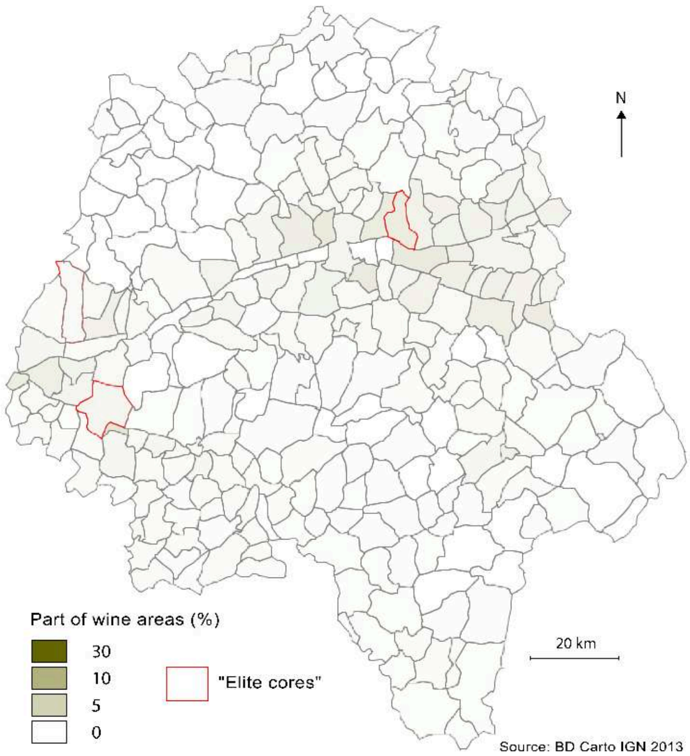
33 The best simulation obtained gives us an average index of 49.45 and corresponds to a consumption weight equal to 2.6. The table below shows that, overall, the model's deviations from actual data are quite small. In particular, we obtain an average difference of 36.55 ha. However, the standard deviation of 103.78 ha shows us that some communes are very poorly simulated by the model. This is confirmed by the cartographic analysis (map 3).

Table 1: Optimal parameter value and indicator results for sub-model 1

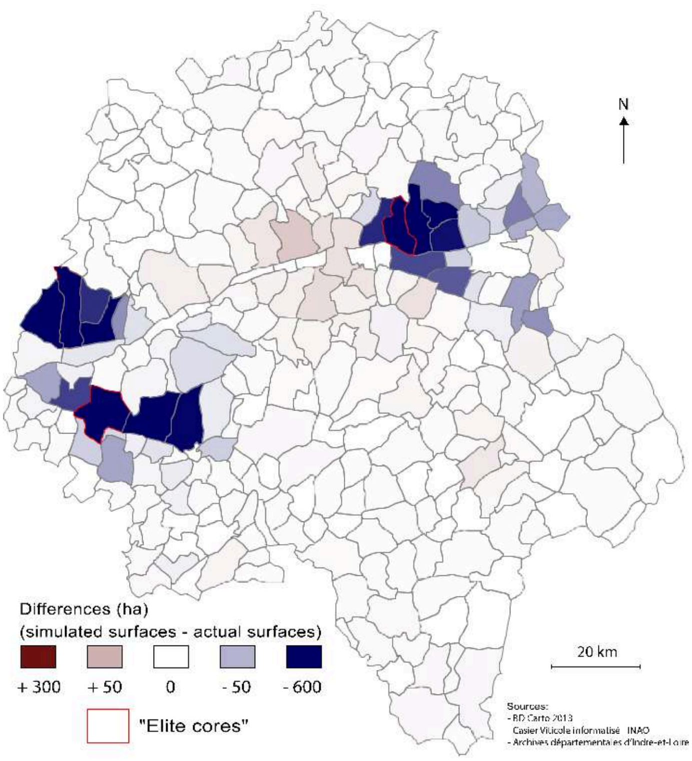
Optimal value	Weight of consumption	2,6
Model quality indicators	Mean of deviations	34,56
	Median of the deviations	1,14
	Standard deviation of deviations	103,78
	Average index	49,45

34 Finally, at this stage, the model simulates a homogeneous and proportional evolution of the wine-growing surface over all the communes (maps 2 and 3). There is no differentiation between the communes, except for the initial wine-growing areas. It can be seen that in order to minimize the differences between simulated and actual areas, the model simulates a very significant decrease in the number of wine-growing areas, which leads to significant differences in all municipalities with a high level of wine-growing activity in 2014, for example Chinon, Vouvray, Bourgueil...

Map 2: Wine-growing areas obtained by simulation for the year for sub-model 1



Map 3: Differences between simulated and actual surfaces for sub-model 1



Consumption and demographics combined with elite core polarization and AOC delineation (sub-model 2)

35 The integration of elite core factors and AOC delimitations into the model increases the combination of possible parameters and considerably increases the simulation time for exploration. Therefore, we carried out a first phase of parameter exploration to find the optimal boundaries. The combination of parameters finally adopted is as follows:

- the consumption weight changes from 3.5 to 4.5 in steps of 0.1;
- the weight of the distance to the elite cores changes from 0.0001 to 0.0005 in steps of 0.0001;
- the resilience factors for communes in AOC, and for those in Touraine, vary from 1 to 1.05 in steps of 0.01.

36 This combination of parameters requires a total of 1980 simulations.

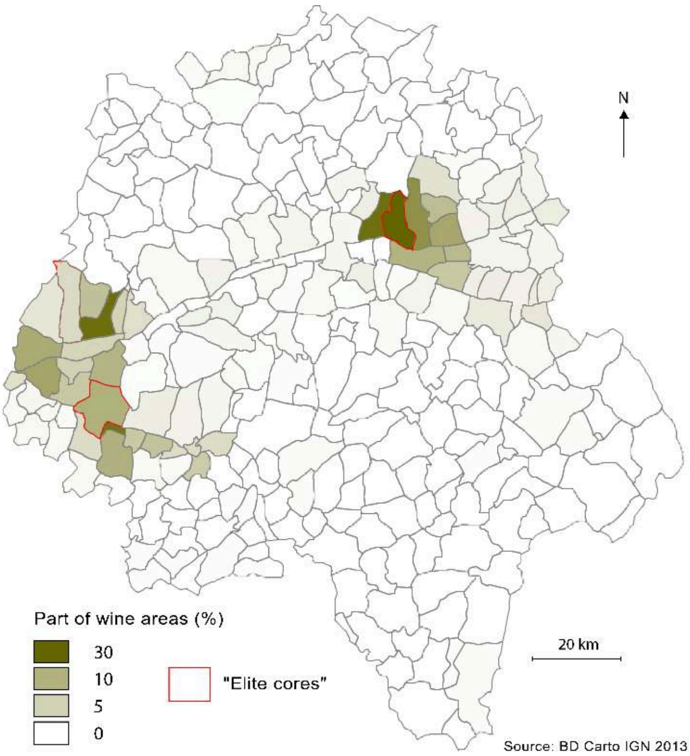
37 Table 2 shows that at this stage, the best simulation obtained shows an average index of 37.78 against 49.45, and more importantly a standard deviation of 87.25 ha against 103.78 in the previous results. We have therefore significantly improved the accuracy of the model.

Table 2: Optimal parameter values and indicator results for sub-model 2

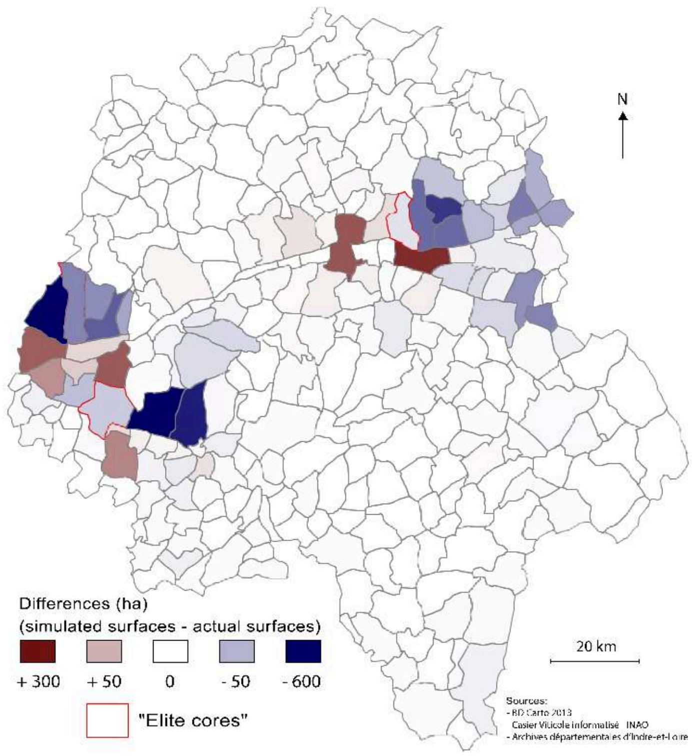
Optimal value	Weight of consumption	4,1
	Weight of core distance	0,0003
	AOC factor	1,04
	Touraine mention factor	1,01
Model quality indicators	Mean of deviations	24,48
	Median of the deviations	1,15
	Standard deviation of deviations	87,25
	Average index	37,78

38 As shown in maps 4 and 5, the spatial differentiation made by identifying elite cores and AOC areas makes it possible to minimize errors in the current production basins, in particular the Vouvrillon, the Cher Valley, the Chinonais and the Bourgueillois. Nevertheless, we observe a wide disparity in results within the production areas. Some municipalities are strongly overvalued (e. g. Montlouis, Chouzé-sur-Loire, Huismes, Ligré) and others are undervalued (Saint-Nicolas-de-Bourgueil, Cravant-les-Coteaux, Panzoult). There is also a significant overvaluation for Tours, which had a large vineyard in the 19th century, which has now disappeared on the north bank of the Loire (an element that the model cannot take into account at this stage). Here the mapping of the vineyards seems much more realistic. We can clearly see the very marked difference between the production basins and the rest of the communes of Indre-et-Loire, most of which have seen their vineyards disappear.

Map 4: Simulated wine-growing areas for 2014 for sub-model 2



Map 5: Differences between simulated and actual surfaces for sub-model 2



Consumption and demography, combined with the polarization of elite cores and AOC delimitation, with consideration of population dynamics (sub-model 3)

39 To take into account the population dynamics of the communes, we have added a population coefficient to the denominator of the general equation: communes that have experienced strong population growth lose a larger share of the wine-growing area. To calibrate this parameter, we also use a weight. To find the optimal value of this weight, we kept the previous set of parameters, to which we added the population density weight, which changes from 0.1 to 0.9 in 0.1 steps. This gives us 17,820 simulations to analyze.

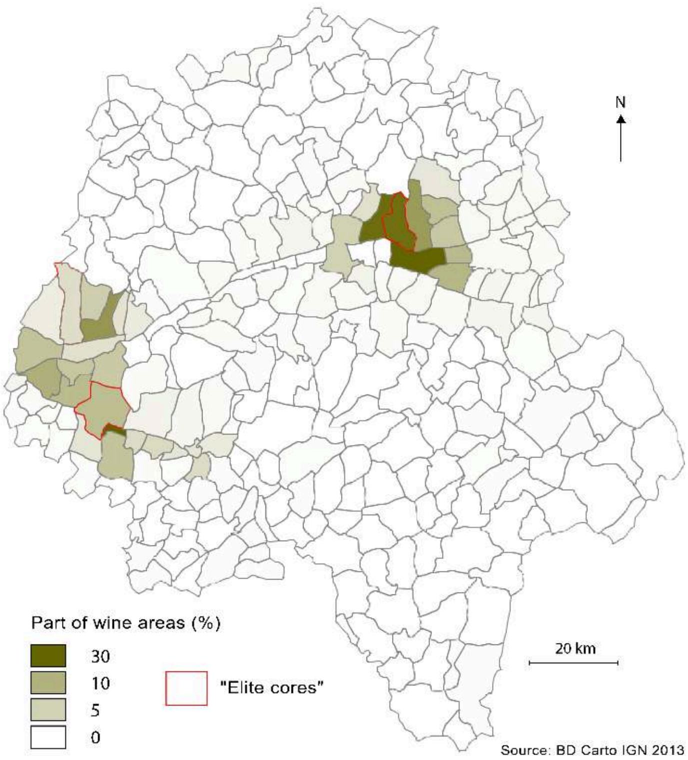
40 Once again, the addition of a new factor improved the accuracy of the model (Table 3). This improvement can be observed on all indicators with a decrease of 2 ha on average (the average index goes from 37.78 to 35.49 ha).

Table 3: Optimal parameter values and indicator results for sub-model 3

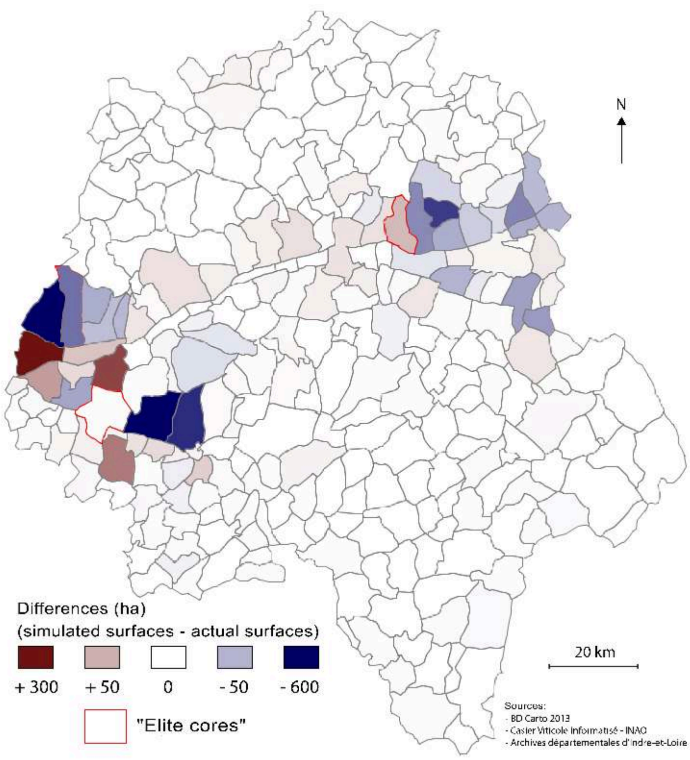
Optimal value	Weight of consumption	4,5
	Weight of core distance	0,0002
	AOC factor	1,05
	Touraine mention factor	1,03
	Weight of population density	0,6
Model quality indicators	Mean of deviations	22,50
	Median of the deviations	0,90
	Standard deviation of deviations	82,50
	Average index	35,49

41 The maps below show that the considerable deviation previously observed for the municipality of Tours has been largely corrected. Indeed, Tours, the only large city in Touraine (with more than 100,000 inhabitants), has experienced significant and continuous demographic and urban growth since the 19th century, a growth that intensified in the middle of the 20th century. We also see a significant improvement for the municipalities of Montlouis, Chinon, Restigné and Bléré. On the other hand, some municipalities have slightly worse results, such as Langeais, Chouzé-sur-Loire, Saint-Patrice, Luzillé and Souvigny-de-Touraine, but also Vouvray, which is slightly overvalued by the model.

Map 6: Wine-growing areas obtained by simulation for 2014



Map 7: Differences between simulated and actual surfaces for sub-model 3



Consumption and demographics, combined with the polarization of elite cores and AOC delimitation, with consideration of population dynamics and the phylloxera crisis (final model)

42 The integration of the phylloxera crisis does not imply the exploration of an additional parameter since, in the model, the factor occurs at a given time (1900) and no longer has any impact thereafter. It just reduces the amount of vineyard land for all the municipalities. We therefore explored the model with the same set of parameters as the previous step, namely:

- the consumption weight changes from 3.5 to 4.5 in steps of 0.1;
- the weight of the distance to the elite cores changes from 0.0001 to 0.0005 in steps of 0.0001;
- the resilience factors for communes in AOC and Touraine vary from 1 to 1.05 in steps of 0.01;
- the weight of population density changes from 0.1 to 0.9 in steps of 0.1.

43 The results of the model with and without taking into account the phylloxera crisis are very similar in terms of the indicators in the final state of the simulation (Table 4). We note that the average index has gone from 35.49 to 35.46, which is almost negligible. On the other hand, it is interesting to note that with this factor, the model reduces the importance of the consumption factor (which largely determines the decline in wine-growing areas). Indeed, the optimal consumption weight obtained with the inclusion of phylloxera is 3.9 compared to 4.5 previously.

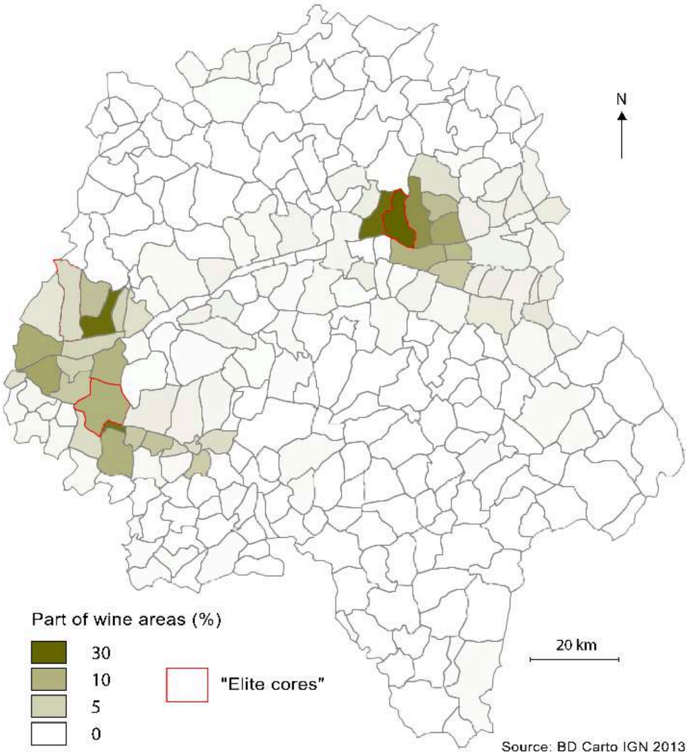
Table 4: Optimal parameter values and indicator results for the final model

Optimal value	Weight of consumption	3,9
	Weight of core distance	0,0002
	AOC factor	1,05
	Touraine mention factor	1,03
	Weight of population density	0,6
Model quality indicators	Mean of deviations	22,47
	Median of the deviations	0,93
	Standard deviation of deviations	82,51
	Average index	35,46

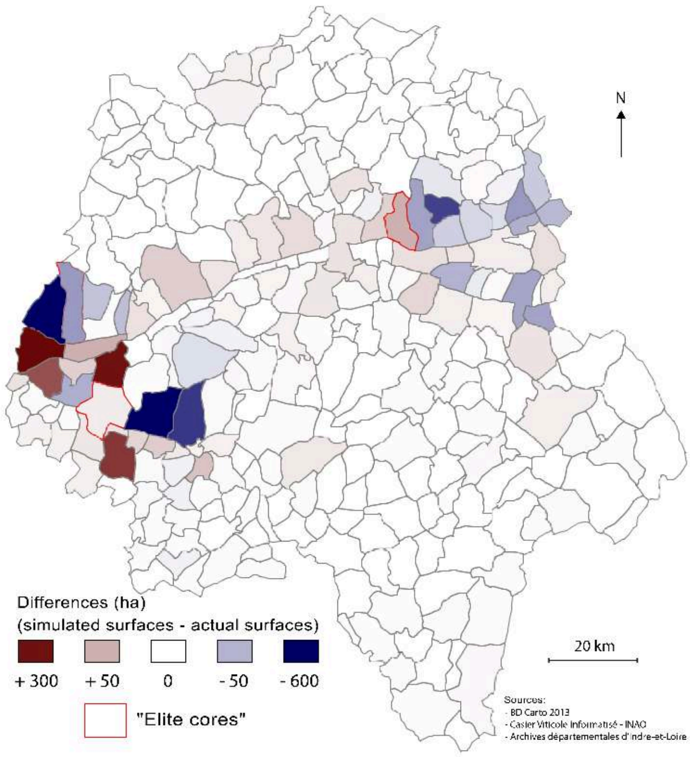
44 From a spatial point of view, there are some changes compared to the previous case. Municipalities such as Restigné and Noizay have been improved, while other municipalities such as Savigny-en-Véron, Langeais, Azay-sur-Cher have slightly larger deviations. Overall, the same disparities are still observed within the Chinonais, Bourgueillois and Vouvrillon, and the strong differences always concern the same communes (e. g. Saint-Nicolas-de-Bourgueil, Cravant-les-Coteaux, Panzoult...) (maps 8 and 9). Taking into account phylloxera makes it possible to obtain a much more

realistic curve of surface evolution at the departmental level. We observe that the weight on the consumption coefficient is lower compared to previous simulations. This shows that, without taking phylloxera into account, the model tends to overestimate the weight assigned to the consumption factor to compensate for the sudden decrease in vines at the end of the 19th century. Thus, taking into account phylloxera makes it possible to obtain a more coherent and accurate model over the entire simulated period (and not just in the final state).

Map 8: Wine-growing areas obtained by simulation for 2014



Map 9: Differences between simulated and actual surfaces for the final model



Synthesis of the results

45 As we have just shown, each factor improves the accuracy of the model. The choice of these different factors and their implementation therefore seem consistent. Finally, the VitiTerroir model (which takes into account four factors) has generally low errors with an average difference of 22.47 ha, a median of 0.93 ha and a standard deviation of 82.51 ha (Table 1).

Table 5: Summary of exploration results for the four sub-models

	Sub-model 1	**Sub-model 2**	**Sub-model 3**	**Final model**
Mean of deviations	34,56	24,48	22,50	22,47
Median of the deviations	1,14	1,15	0,90	0,93
Standard deviation of deviations	103,78	87,25	82,50	82,51
Average index	49,45	37,78	35,49	35,46

46 As shown in Map 10 and Figure 6, the model makes it possible to calculate wine-growing areas in 2014, based on the wine-growing areas in 1836, close to those actually observed for a large majority of the municipalities of Indre-et-Loire. This result tends to show that, on the whole, the processes for explaining the spatial evolutions of the Tours vineyards are relatively simple. Nevertheless, some communes show significant

differences (> 100 ha), highlighting vineyards with particular trajectories over the last two centuries. The combination of the four factors analysed is therefore not sufficient to explain singular, original developments that reveal the intervention of other factors, and more complex explanations that should be sought. The VitiTerroir model confirms the exceptional nature of the spatial concentration of Tours wine growing on a few poles, particularly Bourgueillois and the Chinonais. But the analyses highlight nuances: the vintages of the confluence of the Loire and the Vienne (Savigny-en-Véron), the left banks of the Loire (Avoine, Huisme) and the Vienne (Rivière, Anché, Sazilly, Tavant, Theneuil) are strangely declining, while, against all expectations, two communes that were once little turned towards viticulture are now emerging: Panzoult and Cravant-les-Coteaux. Bourgueillois has an extraordinary consecration that confirms a breakthrough initiated in the second half of the 18th century, but the topographical and pedological factors play a key role here in differentiating the terroirs: the communes at the bottom of the valley (Chouzé-sur-Loire and La Chapelle-sur-Loire), once fully wine-growing, are now disinherited from their vineyard. The extraordinary wealth of Vouvrillon is also contrasting. The VitiTerroir model overestimates the famous vineyards of Rochecorbon and Vouvray: here we can perhaps sense the threatening urban pressure of Tours (Yengué and Chaballier, 2015). On the other hand, the VitiTerroir model highlights the progressive development of the Vouvrillon vineyard to the east, moving away from Tours, along the Loire at Vernou-sur-Brenne, Chançay and Noizay, and to a lesser extent to the north, on the plateau at Reugny. Moreover, VitiTerroir shows that the vineyards on the right banks of the Loire (Nazelles-Négron, Pocé-sur-Cisse, Limeray and Cangey) and Cher (Montlouis, Saint-Martin-le-Beau, Dierré, Civray-de-Touraine), but also the left banks (Mosnes and Chargé for the Loire, Francueil for the Cher) are very resistant. All these vineyards have undergone a singular evolution, highlighted by the VitiTerroir model, which appears to be a tool that reveals muted trends.

Map 10: Differences between the wine-growing areas obtained by simulation and the actual areas identified in 2014

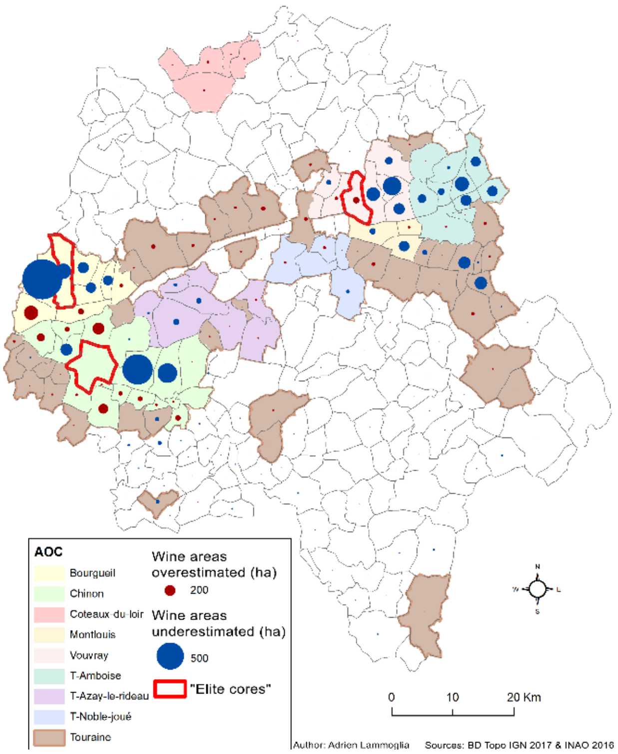
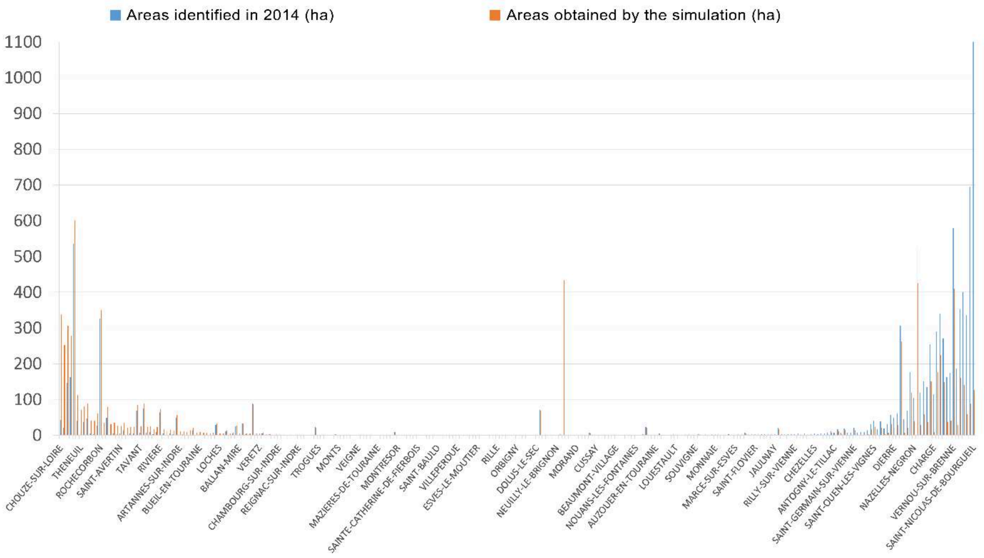


Figure 6: Wine-growing areas obtained by the simulation, compared to the areas identified in 2014 (the communes are sorted according to the differences between simulated and actual data, positive on the left, zero in the centre and negative on the right)



Discussion

47 From a methodological point of view, VitiTerroir is an innovation. It is indeed the first experience of using computer simulation to understand the spatial dynamics of wine on the scale of a French department over a long period of time (more than two

centuries in this case). For a historian, this approach is exhilarating, as it provides the means to simulate the effects of factors, and their combinations, on geographical behaviours by using historical reality as a benchmark to assess the performance of the factor set. It is thus possible not only to confirm or experimentally invalidate, via the simulation platform, the influence of combinations of factors, but also to measure their degree of performance. The comparison of the simulation results with the reality of the historical process highlights areas where the poor simulation results highlight the existence of an underestimated complexity, which is not understood in the explanatory framework underlying the model. VitiTerroir therefore proposes an experimental way of making history: establishing facts from sources, testing explanations, going back to sources to improve the explanatory framework, testing against a more complex model... Modelling makes it possible to bring history into the experimental sciences.

48 The contribution of the VitiTerroir model is not only methodological. It leads to original contributions to the historical knowledge of Tours wine growing in the 19th and 20th centuries. For Touraine, VitiTerroir confirms the general trends in the spatial dynamics of vineyards during the 20th century (Legouy, 2014), namely a very strong polarisation on a few sectors in the AOC: Vouvray, Bourgueil, Saint-Nicolas-de-Bourgueil, Chinon and, to a lesser extent, the appellation "Touraine", particularly in the mentions "Azay-le-Rideau" and "Amboise". But VitiTerroir goes well beyond this confirmation, because it provides an assessment of the performance of this historical movement of vineyard concentration for each commune in the Indre-et-Loire department. It introduces nuance, underlines territorial heterogeneity, and gives counter-intuitive results: in a AOC, some communes (which did not necessarily have an exceptional wine-growing past) stand out and are the driving force, while others, "traditionally" wine-growing, abandon this economic orientation to a certain extent, if not totally,: how can we understand these contrasting developments? How fast are these changes happening? Who are the actors? What are the organizations? VitiTerroir's results point to new historical explorations and original questions.

49 The results of the modelling lead us to deepen our research on the wine-growing areas that have experienced these particular trajectories. It would be necessary to understand the factors that have generated these expansion dynamics for the Bourgueillois and the communes on the right bank of the Vienne in Chinon, and those that have caused the decline or even extinction in the communes on the left bank of the Vienne, or on the left bank of the Loire opposite the Bourgueillois vineyard. On the other hand, the VitiTerroir model reveals an astonishing resistance of the municipalities on the right bank of the Cher and the left and right banks of the Loire at Amboise. VitiTerroir can be improved, taking into account several factors that will undoubtedly prove essential: the importance of social structures (wine cellars, cooperatives, inter-professional organisations, dynamism initiated by strong individuals, generational influence, etc.), the rejection of certain types of soil, the question of exports, etc.

50 Another short-term perspective would be to test the model on a new wine-growing region to assess its replicability. Indeed, VitiTerroir was designed to be easily transposable on French territory. All that is required is to know the wine-growing areas at t0 and tfinal, to know the AOC boundaries and to acquire data on municipal population growth that are very accessible nowadays. In the longer term, the objective of the VitiTerroir program is to provide a geoprospective dimension to the model in

order to identify scenarios for the evolution of French vineyards based on trends and measures that could be taken in the near future, such as the authorization of 1% planting rights, which was launched on January 1, 2016.

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ABSTRACTS

The VitiTerroir project ambitions to develop a model simulating spatial dynamics of vineyards in Centre-Val de Loire region, France. We study these dynamics in the long (several centuries), medium and short term, using historical sources (administrative surveys, field books, cadasters...). In this paper, we focus on the impact of four factors on the dynamics of vineyards in

Touraine over two centuries (1808-2014): wine consumption, the geographical concentration of production, urban growth, and the phylloxera crisis. We want to explore their impacts on the vineyard's areas of each municipality through four sub-models.

By exploring every sub-model, we show that the evolution of the people's consumption practices largely explains the evolution of vineyard areas for the majority of the municipalities (68 %). Moreover, we highlight the resilience of some vineyards (Vouvray, Chinon, Bourgueil) even if the phylloxera crisis has affected all the Touraine region in the 1880s. Finally, we show that urban growth, analyzed through demographic change, sometimes explains the decline of some major vineyards of the 19th century. However, it applies only to a minority of communities close to the city of Tours.
Keywords: geohistory, spatial simulation, spatio-temporal dynamics, vineyard

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